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RESEARCH ARTICLE

Near surface mounted FRP reinforcement for strengthening of concrete structures

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Abstract

This paper is based on literature review regarding fibre reinforced polymers (FRP) used as near surface mounted (NSM) reinforcement for strengthening of concrete structures.

Strengthening of structures is a complex task. Different systems can be used in order to utilize the fibre reinforced polymer in the most efficient way.

Near surface mounted reinforcement is practical alternative to externally bounded reinforcement while it has many advantages.

Keywords

near surface mounted reinforcement · failure modes · strengthening application

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1 Introduction

Increasing requirements for existing concrete structures need enhanced strengthening methods. A high number of structures that will be used in 20 years have been already built. Some of these structures need to be upgraded or replaced, because they are in poor condition, not only due to deterioration processes, but also due to errors made during design and execution [1].

In the last two decades fibre reinforced polymer (FRP) materials have emerged as promising alternative repair materials due to several advantages of FRP strengthening. There is a great potential in FRP strengthening. However, it is important to have sufficient knowledge on behaviour and applicability of different FRP materials and techniques. FRP reinforcements are available in form of circular or rectangular or strips made by pultrusion, or in the form of fabrics made with fibres in one or at least two different directions used in externally bonding wet lay-up technique. Carbon (C), glass (G) and aramid (A) are the main fibres which compose the fibrous phase of these reinforcements, while in most cases in the matrix phase epoxy is used to bind the fibres together.

FRP materials can be bonded to the exterior of concrete structures using high strength adhesives to provide additional reinforcement to supplement the available internal reinforcing [2].

In addition to external bonding, the FRP reinforcements can be inserted into grooves cut into the structural members in an application called generally near surface mounting (NSM) (Figure 1).

The use of NSM reinforcement was developed in Europe for strengthening of RC structures in the early 1950s. In 1948, an RC bridge deck in Sweden needed to be upgraded in its negative moment region due to an excessive settlement of the steel cage during construction. This was accomplished by inserting steel reinforcement bars in grooves made in the concrete surface and filling it with cement mortar [3].

Considering the use of FRP reinforcement instead of steel reinforcement in some applications has many advantages, primary its excellent resistance to corrosion, the ease of application due to lightweight properties, and the reduced groove size due to higher tensile strength and softer surface deformations (stiff deformations of steel induce splitting of the concrete cover) [4].

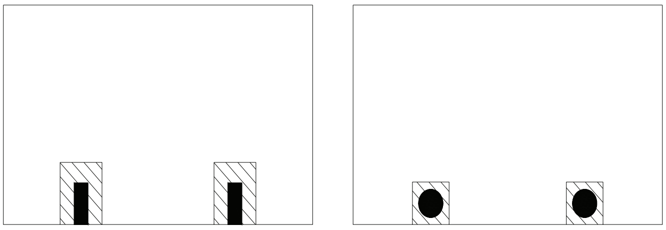

Fig. 1. Near surface mounted FRP, rectangular shapes and rods

Near surface mounting technique has many advantages vs. externally bonding technique (EBR): larger bond surface induces better anchorage capacity, it provides higher resistance against peeling-off, so a higher percentage of the tensile strength can be mobilized, no preparation work is needed other than grooving, therefore reduced installation time will be required, [5, 6]. The FRP reinforcement due to the special mounting setup is protected by the surrounding concrete against mechanical influences, therefore, these technique is attractive for strengthening in the negative moment region. The strengthening has an improved protection against freeze/thaw cycles, elevated temperatures, fire, ultraviolet rays and vandalism. The experiments showed also an improved ductility, preferable composite action, and an ultimate load develop more independent from concrete surface tensile strength [6, 7].

The role of groove filler adhesive is to transfer the stresses between the FRP reinforcement and concrete. Two types of adhesive can be epoxy or cement based. The most relevant mechanical properties of groove filler are tensile and shear strengths. The tensile strength is especially important in case of round bars which induce high circumferential tensile stresses in the epoxy [4]. The shear strength is especially important when the bond is controlled by cohesive shear failure of the epoxy [8]. The best performing groove filler is a two-component epoxy. Their material properties are strongly depending on time and temperature and influences long-term structural behaviour of prestressed near surface mounted carbon FRP strips in service [9].

The cement based adhesive has some advantages vs. epoxy like: it is cheaper, presents reduced hazard to workers and environment, allow bonding to wet surfaces, has a better behaviour at elevated temperatures, and it is compatible with the concrete substrate. The main disadvantage is its reduced tensile strength and during hardening of the mortar adequate wetting should be assured. Bond and flexural test identified some limitations of cement mortar as grove filler [4].

The use of cementitious adhesive is not recommended when cyclic loading is applied during hardening, but it works well when the adhesive is hardened under static load conditions [9].

2 Failure Modes

Several failure modes are known in general for elements strengthened with FRP. Their understanding is important, because they have significant effect on the ultimate load. We need to distinguish failure of concrete members with externally bonded reinforcement and near surface reinforcement.

2.1 Failure Modes of Externally Bonded FRP Reinforcements

Bond is necessary to transfer forces from the concrete in to the FRP, bond failure implies complete loss of composite action. We distinguish four different bond failures: (1) debonding in the concrete cover near the surface along a weakened layer, (2) debonding at the interface between concrete and adhesive, (3) debonding in the adhesive, and (4) debonding between adhesive and FRP (Figure 2).

Peeling-off failure is associated with the propagation of the localized debonding. Peeling-off failures can be distinguished according to the initiation of debonding. Debonding can result in peeling-off at: flexural cracks, shear cracks, unevenness of the concrete surface and in the anchorage zones [2].

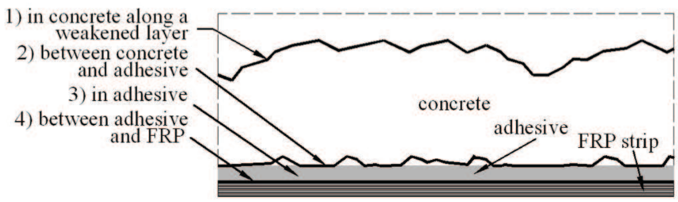

Fig. 2. Interface bond failure modes for EBR FRP strips

2.2 Failure Modes of Near Surface Mounted FRP Reinforcement

2.2.1 Interfacial Failure Modes

Interfacial failure modes can develop in two modes as a pure interfacial failure or as a cohesive shear failure in the adhesive. Pure interfacial failure can be identified by the absence of adhesive remained at the FRP surface after failure. Cohesive shear failure can be identified by the presence of adhesive on both FRP and concrete after failure.

Failure at reinforcement adhesive interface

The pure interfacial mode can be critical for bars with smooth or lightly sand-blasted surfaces, when the bond relies on adhesion instead of mechanical interlock between bar and adhesive [8] [10].

Failure at the epoxy concrete interface

Interfacial failure was found critical only in case of precast grooves due to their even surface (Figure 3). When this type of failure develops the bond stress is lower than usual, but failure is more ductile due to the residual friction at adhesive and concrete interface [4].

2.2.2 Cover Splitting

The mechanism of cover splitting in case of round bars is similar to the splitting bond failure of steel deformed bars, but due to

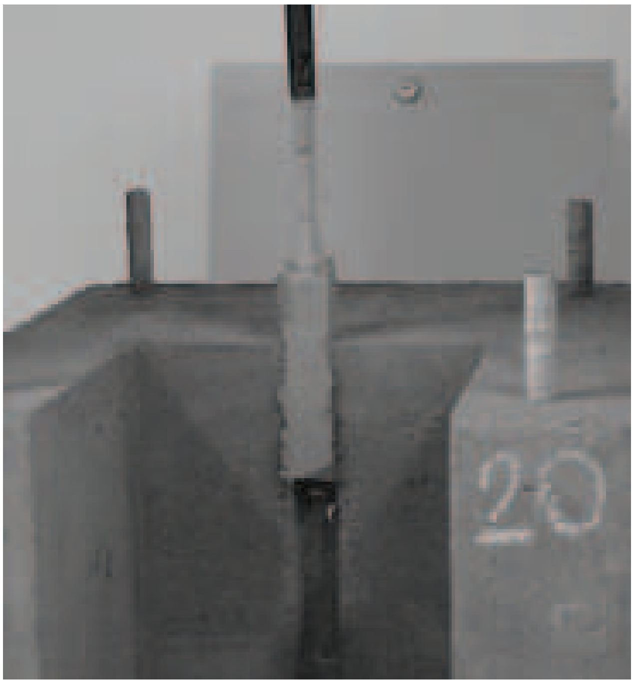

Fig. 3. Failure at epoxy concrete interface [4]

the softer deformations of the FRP bars the splitting tendency is not as intense. Splitting is caused by the radial component of the bond stress. Multiple types of cover splitting were observed, in case of epoxy adhesive concrete cracking and concrete cracking accompanied by longitudinal splitting of the adhesive, in case of cementitious mortar adhesive splitting of the adhesive was dominant influenced by the low tensile strength of the filler material [4]. However, in case of NSM strips the perpendicular component of interactional stress acts towards the thick lateral concrete (exception are reinforcements close to the edge) so splitting failure is less likely to appear [8, 10].

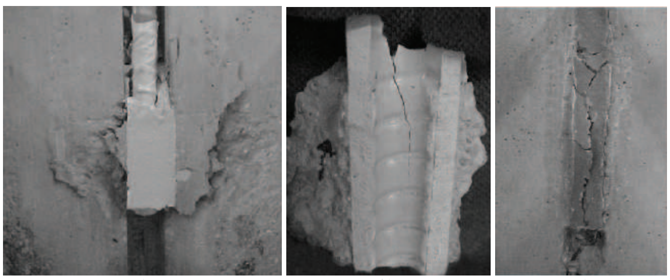

Fig. 4. Cover splitting failure of NSM round bars a) concrete cracking b) concrete cracking accompanied by longitudinal splitting of the adhesive c) splitting of the adhesive [4]

2.2.3 Edge Splitting

Edge splitting failure can be critical in elements where the reinforcement is close to the edge of the concrete member. It is induced also by the development of interactional stress. Edge splitting failure can be avoided by keeping a minimum distance from the edge; this should be considered in design [8, 10]. In the author's opinion thermal expansion differences between epoxy and concrete can influence edge splitting and it should be considered, although further experiments are needed.

2.2.4 FRP Tensile Rupture

Tensile rupture (it has been rarely observed by nonprestressed strengthenings) should be avoided according to its explosive nature. Structures strengthened with prestressed FRP more frequently fail by fibre tensile rupture because by prestressing the FRP we use a portion of its strain capacity [1].

3 Detailing

Detailing of the near surface mounted reinforcement is an important issue; we need to select the most suitable FRP cross section and adhesive. In design there should be considered the minimum distance between adjacent reinforcement to avoid horizontal propagation of the splitting cracks, and the minimum distance from the edge of the member to avoid edge splitting effect [11].

Application of near surface mounted FRP reinforcement consists of the following working steps.

In the first step a groove is cut using a saw with one or two diamond blades or a grinder with dimensions in function of the reinforcement size and type. Further preparation of the groove consists of cleaning the surface from dust and lose parts using vacuum or compressed air, then the groove is filled halfway with adhesive, afterwards the FRP rod/strip is inserted and lightly pressed to let the adhesive flow around the FRP. Finally, the groove is filled with more paste and the surface is levelled [5].

The minimum dimension of the grooves should be taken at least 1.5 times the diameter of the FRP bar. When a rectangular bar (strip) with large aspect ratio is used, the minimum dimensions must be 3 times the bar width and 1.5 times the bar hight (Fig. 5) [12]. In other instances, the minimum groove dimension could be the result of installation requirements rather than engineering. For example the groove width may be limited by the minimum blade size and the depth by the concrete cover. We should always avoid cutting of the existing steel reinforcement. Optimal dimensions of the groove may depend on characteristics of the adhesive, surface treatment of FRP, and concrete tensile strength, surface, aggregates.

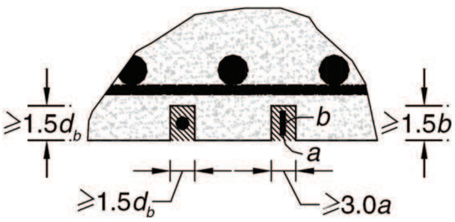

Fig. 5. Spacing of the NSM reinforcement [12]

Spacing of FRP shear reinforcement should not exceed $l_{net}/2$, or 600 mm (Fig. 6). To prevent crushing of concrete, the total

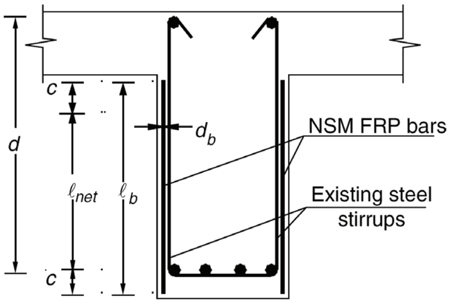

Fig. 6. Shear strenthening [12]

reinforcement contribution taken as the sum of both steel and FRP reinforcement should be limited [12].

4 Experimental Results and Applications

In this chapter there is a review of some experimental and in situ NSM polymer strengthening.

4.1 Comparative Study on Slab Elements

These are probably the most well known test results on early studies of NSM. It is a comparative study using EBR vs. NSM reinforcement on slab and beam elements [11]. The bending moment vs. deflection indicates considerable increases both for maximum moment and for maximum deflection in case of NSM reinforcement (Figure 7).

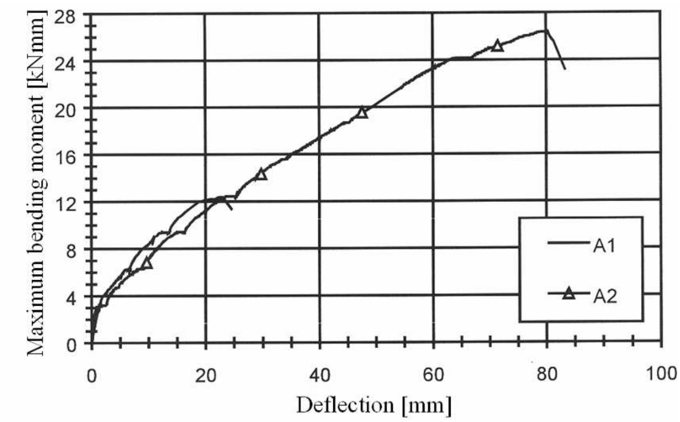

Fig. 7. Bending moment vs. deflection curves for slab elements [4]

4.2 Strengthening of Reinforced Concrete Beams

4.2.1 Flexural Strengthening

Flexural strengthening represents the most popular application of FRP reinforcement.

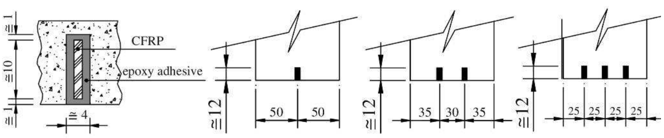

Fig. 8. Detailing of flexural strengthening carbon FRP strips [14]

In Portugal carbon FRP strips were applied on RC beams as result they doubled the ultimate load of the corresponding reference beam (Figure 8). They increased the load with 32% to 47% at the onset of steel reinforcement yielding. The increase on cracking load was also considerable. The strengthened beams showed a higher stiffness between the cracking and yielding load. The collapse of the beams started with sliding of the carbon FRP strips. It was characterized by the detachment of a concrete layer at the bottom of the beam. The maximum strains registered in the FRP ranged from 62% to 92% of its ultimate strain, showing the good anchorage capacity of the near surface mounted laminates and optimal use of the reinforcement tensile capacity [14]. Similar experiments were done in Poland, they confirmed the results of the previously presented test [7].

A special test indicated if the axial stiffness of NSM aramid FRP rods were similar to the EBR aramid FRP sheet stiffness, the flexural reinforcing effect may be similar too [15].

4.2.2 Shear Strengthening

Shear failure depends on several parameters, it should be avoided owing to its brittle nature. The use of FRP in shear strengthening introduces new complexities, namely: FRP-concrete bond condition, linear elastic material behaviour, and the different strengthening techniques and arrangements that can be used. Test run in Portugal studied on RC T beams the strengthening effect of carbon FRP strip quantity (Figure 9) and orientation. The strips at 60° orientation were the most effective, it assured an average increase in service load (deflection of L/400) of 24% compared to the simply RC and 14-15% compared with the beams strengthened with strip orientation 90°and 45° (Figure 10).

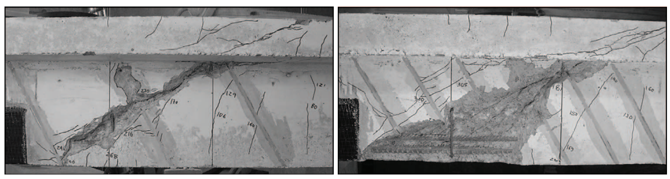

Fig. 9. Failure of shear strengthened RC beams with a. 3 reinforcing b. and 7 reinforcing carbon FRP strips with 60°orientation [16]

The largest increase in service load (30%) was registered at beams with the highest percentage of reinforcing strips (Figure 6. b). This tendency was not observed in the series of beams with strips orientation of 45° [16].

Behaviour of RC beams strengthened in shear with NSM FRP reinforcement was studied in other experiment with similar results. The use of strips instead of round bars resulted in a lower FRP contribution to the shear capacity. As failure was in all cases separation of the concrete side cover at steel stirrups level, decreasing the spacing or increasing the inclination did not benefit the shear capacity of the beams [17].

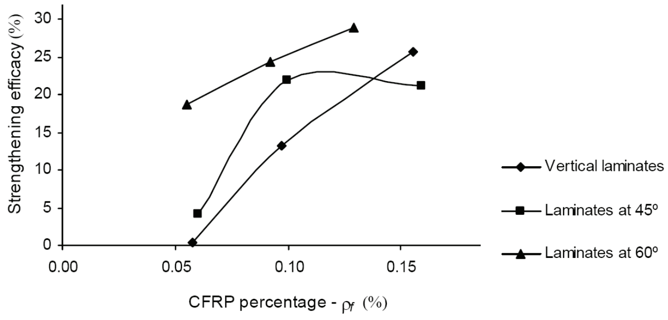

Fig. 10. Strengthening efficacy vs. carbon FRP percentage [16]

4.3 Column Strengthening Experiments

Columns of reinforced concrete framed structures are important elements since their failure leads to collapse of the structure.

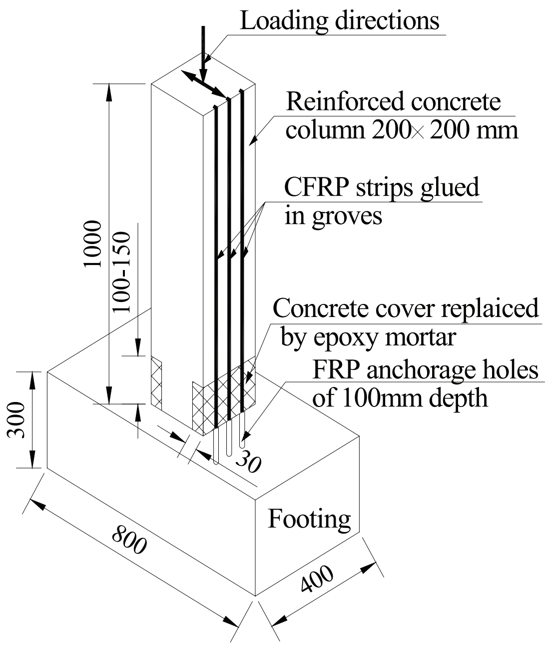

Fig. 11. Strengthening technique in specimens of RC column [18]

To asses effectiveness of NSM strengthening three series of RC columns (non-strengthened columns NON, strengthened with CFRP strips PRE, tested columns of the NON series strengthened with CFRP strips POS) were loaded with static axial compression load and cyclic horizontal load. The strengthening technique presented some particularities (Fig. 11) firstly the concrete was removed from the non-linear hinge region (100-150 mm from the column bottom) and was replaced by epoxy mortar, the groves were cut along the faces subjected to tensile stress and in the alignment of the grooves perforations of about 100 mm were made in the footing to anchor the FRP reinforcement. The test showed a significant increase of the load carrying capacity of both PRE and POS strengthened columns [18].

4.4 Silo Repair and Upgrading

An innovative and cost-effective solution utilizing near surface mounted FRP rods was used for upgrading six cement silos located in Boston area (Figure 11). An inspection revealed concrete spalls and structural cracks at the reinforced concrete silos caused by the missing of approximately 30% of the designed vertical and hoop steel. Full access around the outside perimeter was not possible, the silos were built in cluster formation of 4 and 2 silos.

The major benefits of near surface mounted FRP rods are the following:

- minimized groove dimensions due to the high strength and resistance to corrosion of the bars,
- good anchoring possibilities,
- the rods which were doweled into the common silo walls to a depth that ensured development of their strength,
- lightweight of the FRP made possible the mounting of the 45 m bars in one pieces [5, 19, 20].

Fig. 12. Groove cutting and doweling of the FRP into a common wall [19]

4.5 Strengthening Using Prestressed FRP

By presterssing a higher utilization of the FRP material is possible, which is extremely important to ensure the proper force transfer to the structure. In case of near surface mounting the shear and normal stresses can be more efficiently transferred to the structure without mechanical anchoring devices.

There are some advantages of prestressed FRP application, firstly the better utilization of the strengthening material. Higher first cracking load, smaller crack size and distance between the cracks will most likely increase the durability and stiffness of the structure. Unloading of the steel reinforcement improves the fatigue behaviour. Higher steel yielding and ultimate load with smaller midpoint deflection are also in favour of prestressing. However there also exists a drawback. The majority of the FRP materials are linear elastic up to failure. By prestressing them we use a portion of the strain capacity. This fact explains also that in most cases the structures strengthened with prestressed FRP fail by fibre rupture.

Figure 13 shows the typical behaviour of beams in four point bending. The figure shows three important stages, concrete cracking, internal reinforcing steel yielding and finally failure [1, 21].

5 Conclusions

Present paper gives an extensive literature review for behaviour and possible applications of near surface mounted

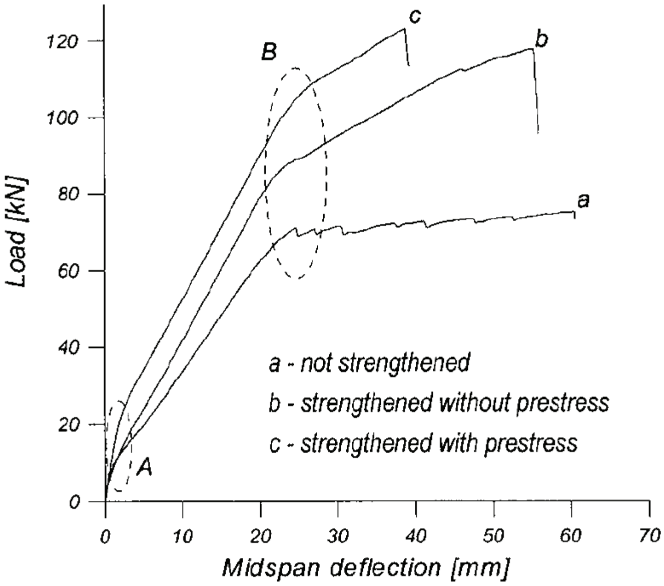

Fig. 13. Load-deflection diagram of beams strengthened in flexure with carbon FRP [1]

(NSM) reinforcements. NSM is a new type of strengthening in addition to externally bonded reinforcement (EBR). In structural behaviour of flexure and shear strengthened RC beams, the same amount of NSM reinforcement provides higher load bearing capacity and higher deflection up to failure compared to EBR.

Elements strengthened with NSM reinforcements show different failure modes than EBR due to the larger bond surface and the improved anchorage capacity of the fibre reinforced polymer (FRP) elements.

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